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Realtime Characteristic of FF Like Centralized Control Fieldbus and Its State-of-Art¹

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Abstract -- The temporal property of MAC protocol of fieldbus is critical to meet real-time constraints of field devices in factory floor. Among various types of MAC protocols, the one using centralized strategy is characterized by providing feasible schedule to meet different temporal constraints of field devices online, but also providing schedulability analysis offline a priori. WorldFIP and FF, two popular international standards of fieldbus, both adapt centralized strategy, which is mainly implemented by schedule table (ST). This paper mainly discusses how to construct ST, including size of ST, schedule algorithm and schedulability analysis, to meet requirement of field devices on response time, jitter, synchronization, and its State-of-the Art.

1. INTRODUCE

The system, which supports real-time application and meets time constraint requirement, is defined as real-time system. Real-time system is characterized by the correctness of its tasks depending on both their logical results and the time at which these results appear. DRTS (distributed real-time system) consists of lots of distributed nodes on which tasks usually reside and communicate with one another through message transfer to accomplish a common goal. So the ability to providing timely message delivery and predictable inter-task communication is of great importance to a underlying network and protocol since it is difficult to ensure timely results of tasks in a DRTS without the network that supports the timely inter-task messages. (H.Koptez 1997; C.Bottazzo 1997; Tindell 1997) . For guaranteeing realtime constrains of the tasks, normally special-purposed real-time communication networks are applied in DRTS.

The increasing complexity of control systems, as well as the large dimension of controlled processes, has lead to the development of control systems into DCS (distributed control systems). In classic DCS, communication between producer and consumer processes is organized on several functional levels. The lowest level, refers to field level, is the one whose processes have the most temporal constraints on account of the interaction between the controller (such as PLC), sensor and actuator. For flexibility and cost reasons, DCS of field level is applying communication network and

intelligent instrument concept, wherein new control architecture is mainly replacing traditional point-to-point direct connection between controller and field devices with shared communication network. Therefore, the DCS in the lowest level is one of typical (DRTS), where the communication network to support real-time traffic among field devices refers to fieldbus. Obviously, fieldbus is one of typical real-time network since it is infrastructure of communication of the lowest level in factory floor (Fayad 2000).

For a message within fieldbus, the time duration from its release to its completion, refers to its response time, must meet its constraints or deadlines. In fact, the total response time mainly consists of four parts, generation delay, queuing delay, transmission delay and process delay. Normally, queuing delay is dynamic and is determined by MAC (Medium Access Control) mechanism of fieldbus. Therefore, the real time capability of fieldbus, specially the temporal property of its MAC, plays an important role to DRTS. According to strategy for managing message transmission onto network media, MAC of fieldbus can be divided into event-triggered and time-triggered (Wang 2000). The former does not support the real-time application directly and usually uses CSMA (Carrier Sense Multiple Access), like CAN and LON. The latter supports the real-time application directly and can further mainly sub-divided into two kind of strategies for managing message transmission, 1) centralized strategy, such as WorldFIP, TTCAN and FF; 2) distributed strategy, such as PROFIBUS and P-Net.

Within distributed strategy, the temporal constraint of a message is guaranteed by controlling operation period of all nodes in a network, such as the token rotation time in FDDI and PROFIBUS (Jonson 1987). However, distributed strategy is still disadvantageous in its lower accuracy. Jonson ever deduces that the response time of a message in FDDI varies between its transmission time to the double token rotation time. By the way, distributed strategy is still not convenient for adjusting parameter of network when nodes being left or added. The above disadvantage is

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overcome by centralized strategy, which is characterized by the presence of a processing unit whose task is to manage the bandwidth available for transmission, distributing it among all the transmitting nodes, and respecting their time constraints. Applying centralized strategy, the processing unit gives feasible schedule to meet different temporal constraints of messages online, but also gives schedulability analysis offline priori.

Centralized strategy is mainly implemented by ST (schedule table). ST contains a feasible schedule, by which the centralized processing unit schedules transmission of messages in different nodes. This paper mainly discusses how to support real-time communication of FF-like centralized control fieldbus through applying ST and the State-of-the Art.

2. REAL-TIME CHARACTERISTIC CENTRALIZED CONTROL FIELDBUS

FF-like centralized control fieldbus, mainly manages real-time message communication according to PDC (Producer/Distributor/Consumer) model. At any time, only an active node responds for the message communication and makes the arbitration in one segment, this node is called BA (Bus Arbitrator) and (LAS Link Active Schedule) within FF and WorldFIP respectively.

2.1 Producer/Distributor/Consumer Model

PDC model is a management model of messages communication, which adopts centralized MAC (Song 1991). In this case, producer sends process variable, consumer receives the process variable. All transactions are centrally managed by the distributor, which facilitates the respective scheduling in order to meet the temporal constraints required to assure both the temporal accuracy and coherence of the real-time database.

In PDC model, every process variable has only one producer, but probably has several consumers. If a node can provide process variable, it must have function of producer and can transmit process variable to consumer assorting with arbitrator. Firstly, arbitrator gives the bus access to a producer. After obtains the access, the producer will broadcast the messages in its segment, all nodes in this segment can receive this message. The message is received and only reserved in those nodes who need the message, and other nodes will cast off the message. Commonly, relationship between producer and consumer is confirmed by in configuration phase. Producer-consumer model is indicated in Fig.1.

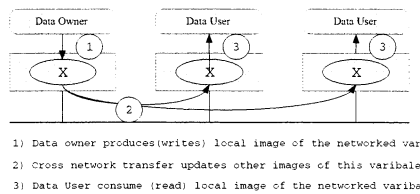


Fig.1 Producer-Consumer Model

2.2 Characteristic of MAC of FF and WorldFIP

2.2.1 MAC of FF

FF and WorldFIP explicitly differentiate periodic and

aperiodic messages, and give the different control strategies respectively, since the diversity of and the importance of real-time guarantee of message communication.

For effectively providing real-time transfer of message and utilization of fieldbus, FF controls transmission of messages onto the bus through a deterministic centralized bus scheduler called the LAS in its MAC. LAS controls message transfers through token, which gives devices access to bus and is hold by at most one device at any time. LAS provides two types of specified token, CD (Compel Token) and PT (Pass Token).

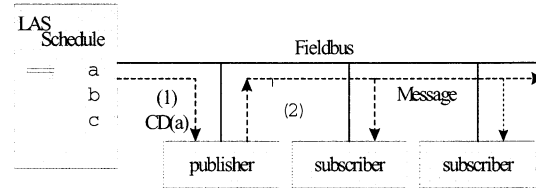


Figure 2. Scheduled message communication in FF.

The CD serves the scheduled messages communication. The LAS has a pre-defined STL (schedule time list) of transmit times for all buffers data that need to be transmitted cyclically. When it is time for a node to send a buffer data, the LAS issues a CD message to the node. Upon receipt of the CD, the device immediately broadcasts or "publishes" the data in the buffer to all devices on the fieldbus. Any node that is configured to receive the data is called a "subscriber". Scheduled data transfers are typically used for the regular, cyclic transfer of control loop data between nodes on the fieldbus, and they have stringent time constraints and are scheduled at determined time according to STL. Figure 2 shows the scheduled message communication.

2.2.2 MAC of WorldFIP

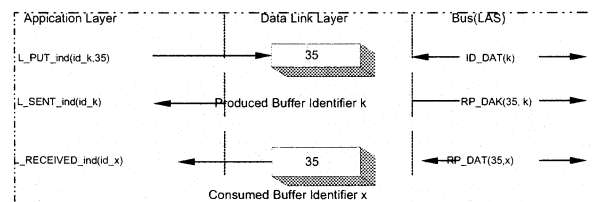


Figure.3 Scheduled message communication in WorldFIP.

In order to manage transactions associated with a single variable, a unique identifier is associated with each variable. The MAC of WorldFIP is made up of a set of produced and consumed buffers, which can be locally accessed through AL (application layer) services or remotely accessed through network services. The latter is concerned with managing network media for information exchange. When produced and consumed buffers are remotely accessed through a network transfer (service also known as buffer transfer), the bus arbitrator broadcasts a question frame ID_DAT, which includes the identifier of a specific variable. The DLL of the device that has the corresponding produced buffer responds with the value of the variable using a response frame RP_DAT. The DLL of the device that contains the produced buffer then notifies the local AL with a (L_SENT_ind). The DLL of the station(s) that has the consumed buffers accepts the value contained in the RP_DAT, overwriting the previous

value and notifying the local AL with a $L_RECEIVED.ind$.

2.3 Schedule Table and Schedule Algorithms

Owing to the deterministic temporal characteristic of periodic message, BA or LAS utilizes ST of transmit times for all periodic messages to manage their communication. According to the characteristic of periodic message, such as time interval, execute time, required deadline and importance *et al.*, ST is built by using a related real-time schedule algorithm and stored in BA or LAS. In operation phase, BA or LAS scans ST constantly and sends the bus access (such as CD or ID_DAT) to producer according to scheduling time of periodic message transmitting service in ST.

Generally, for a periodic message τ_i , it can be denoted by (E_i, D_i, T_i) , where E_i , D_i and T_i are respectively defined as its execute time, deadline and arrival period.

Table.1 Example set of periodic message

Variable Identifier	A	B	C	D	E	F
Periodicity (ms)	1	2	3	4	6	12
Cp^i (100 μs)	2	2	2	2.5	2.5	3

Assume an example that a DCS with 6 periodic messages shown in Table.1, the DCS interconnected by a WorldFIP or FF. A feasible schedule meeting real-time requirements of these periodic messages in table.1 is illustrated as Fig.4.

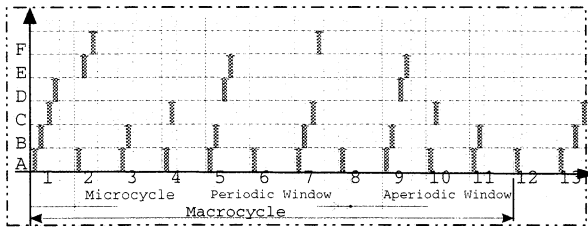


Fig.4 A feasible schedule for periodic messages in table.1

3. STRUCTURE OF SCHEDULING TABLE

For a schedule implemented in ST is mainly concerned with structure (including size of ST), schedule algorithm and schedulability analysis. Raja (Raja, Noubir, 1993) first researches ST under the harmonic hypothesis. Harmonic means the periods of all periodic messages are harmonic, i.e., the following relation always holds: $\forall i, j: 1 \leq i, j \leq g, D_i \geq D_j \Rightarrow D_i = k \cdot D_j, k \in \text{Integer}$. Then, other researches on arbitrary periodic messages are done.

3.1 Basic schedule table under periodic messages being harmonic

Raja (Raja, 1993) first researches the schedule problem of ST in a master, corresponding to BA or LAS in the case of FF and WorldFIP. Raja provides two types of different schedule policies, according to the way of the master handling periodic messages in network, MoPS (Monocycle Polling Scheduling) and MuPS (Multicycle Polling Scheduling). In MoPS, the master uses a single cycle for polling all messages required for transmission in this network. The single cycle just refers to monocycle here. Within the whole monocycle, the

messages are polled using Time Division Multiplexing, which means reserving time slot for every messages required for transmission. The main disadvantage of MoPS is its lower utilization of network bandwidth, since MoPS reserves time slot for every message during the monocycle even if the reserved time being is useless for the message in the monocycle. In fact, a message maybe polled multiple times within its period under the case of using MoPS. Further, in order to solve the limitation of MoPS, Raja proposes MuPS, which is differentiating the cycles used by master to poll messages, according to the period of periodic messages. Actually, the idea of MuPS is activated from the fact that an instance of a message only require be polled once during its arrival period instead of multiple times, that leads to the low utilization of MoPS. As for solving the scheduling problem of MuPS, Raja proposes two best-known scheduling algorithms, RMM (Rate Monotonic Multicycle) and EDFM (Earliest Deadline First Multicycle) under the harmonic hypothesis. Under this hypothesis, MuPS (including RMM and EDFM) consists of harmonic polling cycles. That is there is a minimum cycle coinciding to the shortest period, referred to primary cycle; the duration of other cycles, referred to secondary cycle, are multiples of that of primary cycle.

3.2 Basic approach of building Structure of Scheduling Table for arbitrary periodic messages

However, in actual engineer context, the periods of most periodic messages are arbitrary, the use of RMM and EDFM is limited. For solving the scheduling problem for arbitrary periodic messages, the size of ST and scheduling algorithms must be researched in detail.

Structure of ST is the basis of periodic message scheduling, at the same time, it relates with system memory nearly. Under the harmonic hypothesis, it is easy to determine primary cycle and the size of ST. When periods of periodic messages are not harmonic, there is still an approach to construct ST, wherein the polling cycles are harmonic. This type of polling cycles refer to generalized harmonic polling cycles since the least unit of schedule in ST is not confined to the least period of periodic messages, the primary cycle in the case of harmonic hypothesis. Normally, the least schedule granularity of BA or LAS scanning ST refers to microcycle, and the minimum duration during which the sequence of microcycle is repeated refers to macrocycle. It is obvious that the pair of microcycle/macrocycle determines the size of ST. A well adapted approach for constructing microcycle/macrocycle is based on HCF (the highest common factor) and LCM (the least common multiple) of periods of the required periodic messages.

For a set of periodic messages, $\Omega = (M_i) (M_i = (E_i, D_i, T_i))$, let N_{Mic} denote micorcycle of this set, and let N_{Mac} denote the number of micorcycles within a macrocycle of this set. Then, for a set of periodic messages in Table.1, N_{Mic} and N_{Mac} get the value of 1ms and 12 respectively if ST is constructed according to the rule of HCF/LCM.

3.3 Size of ST and its Optimization

Known from the above section that for a set of periodic messages, size of ST relates with the microcycle and

macrocycle of periodic messages. Size of ST is related to memory of field devices, which often have small memory. When periods of this set of periodic messages are different and even relative prime, the size of ST will become very large if we still apply the rule of LCM/HCM to build the ST. The direct consequence is not only increasing the cost of field device caused by required large memory, but also is not convenient for managing periodic messages caused by overhead of large ST. Therefore, the size of ST is critical for practical engineer application, and must be optimized.

When macrocycle is not confined to LCM of period of periodic messages, there will be shift of relative position for periodic messages in ST within different macrocycles caused by the size of ST (T_s) not being multiple period of periodic messages. The shift will cause loss of information of instant for scheduling periodic messages. For solving the above problem, the theoretical condition which allows the size of ST to be drastically reduced, yet still guarantee temporal constraint of periodic messages is researched (Cavalieri 1995). According to the given theoretical condition, an online algorithm which determines a transmission sequence for each instance of periodic messages is proposed. Through reconciling the advantages of both static and dynamic scheduling, an approach called PS (Planning Scheduling) is presented (Almeida 1999). Utilizing PS, ST is moved on to a dispatch table within a cycle, and meanwhile both dispatcher and scheduler are triggered for another cycle. These cycles are called plans. PS can be characterized as dynamic table-based from full scale, but it is static in one plan. So the PS is a compromise between two extreme situations. Because the size of plan is settled, the overhead of physical memory is decreased. PS has gotten successful application in the scheduling of WorldFIP and CAN.

4. BASIC SCHEDULING ALGORITHM

4.1 real-time capability analysis of periodic messages

At the aspect of periodic message, real-time capability mainly depends on the content of ST, so it is critical to build a proper periodic message scheduling, which means the structure of ST and scheduling algorithm are important.

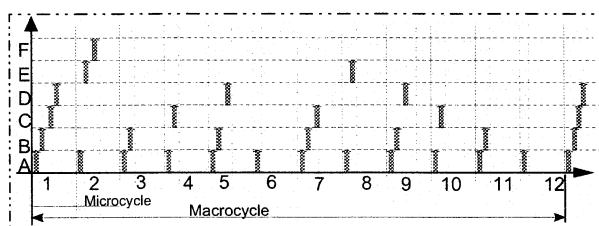


Fig.4 A RM schedule for the periodic messages in Table.1

Scheduling algorithm mainly adopts RM (Rate Monotonic) and EDF (Earliest Deadline First), they are the best algorithms in fixed priority and in dynamical priority scheduling respectively (Burns 1991).

Taken a set of periodic messages in table.1 as example, a RM algorithm given for this set of periodic messages is illustrated in Fig.4.

4.2 Scheduling Algorithm and Schedulability Analysis of Periodic Message

For a scheduling algorithm, schedulability is defined as the analysis, which allows expressing guarantees that all tasks will be scheduled under this scheduling algorithm meeting the respective timing constraints (Ramamritham 1994). Schedulability analysis mainly bases on task response time and utilization. The advantage of former can get the response time of every task and the latter can decrease the overhead.

● Utilization-Based Schedulability Analysis

Liu *et al.* firstly study RM algorithm and give the utilization-based schedulability condition (Burns 1991). In order to reduce pessimistic factor in Liu's result, a bound is proposed (Bini 2001). Unfortunately, the result only adapt to any n periodic messages whose periods are hyperbolic or 2 periodic messages with arbitrary period. In communication system, the main message scheduling approach is non-preemptive, but the presented algorithm given by Liu *et al.* only applies for the pre-emptiveness. After considering the blocking, which is caused by low priority messages, the schedulability condition of RM algorithm in the non-preemptive task scheduling is presented (Buttazzo 1997).

Liu *et al.* give the utilization-based schedulability condition for EDF algorithm, but the condition is only to apply in preemptive task scheduling. After taking the blocking caused by low priority tasks into account, Baker advances utilization-based schedulability condition for non-preemptive EDF algorithm (Buttazzo 1997).

● Task Response Time-Based Schedulability Analysis

Task response time based schedulability condition for RM algorithm is presented in (Audelay 1993), where schedulability condition for non-preemptive RM algorithm after considering the task blocking is also proposed.

Aiming at task response time in dynamic priority scheduling, the worst-case response time being sure under i order deadline processor busy is pointed out, that reduces overhead of finding worst-case response time (Buttazzo 1997).

5. SCHEDULING ALGORITHM IN SYNCHRONOUS PHASE

In real-time system, the requirements of applications for synchronous phase and messages communication are different. FF and WorldFIP both provide synchronous and asynchronous phase to support periodic messages communication. Under the asynchronous phase, BA or LAS continually processes periodic messages which are waiting to be sent, until all messages are sent. Under the synchronous phase, if the current microcycle capability can't send a periodic message, then next microcycle to be researched until a microcycle being capable to send the periodic message. The left microcycle capability is used for other transactions instead of periodic message or keep idle.

Realization of periodic message scheduling algorithm and schedulability analysis change greatly under synchronous phase or not. Under asynchronous phase, the effect of the constraint of microcycle can be neglected, so the result available of uni-processor task scheduling, which is concluded in the section 4.2, can be used directly. Under synchronous phase, however, the blocking caused by low priority for high priority messages can be cancelled because

periodic messages are scheduled and sorted at the beginning of each microcycle. That means the scheduling algorithm and schedulability analysis are no relationship with the preemptive or not. Furthermore, the convenient schedulability analysis of scheduling algorithm is worked out based on processor busy (in this paper, processor is LAS or BA, general, processor busy is defined as time interval of two continual processor idles.). But influenced by idle frame under synchronous phase, the current related results can't be applied directly. some researches on the new problems that caused by synchronization has be done (Almeida 1999, Wang 2000).

Although there have idle frames under synchronous phase, its schedulability condition has some relationship in two modes for the same set of periodic messages.

- Utilization-Based Schedulability Analysis

Utilization-based schedulability analysis has advantage of low computation overhead and can be applied in the admission control of new periodic message, although it is imprecise and has some conservative factors. Under the precondition of maintaining low computation overhead, to decrease the conservative factors in utilization-based schedulability analysis is critical. For a set of periodic messages, through constricting relationship of the same set under synchronization and asynchronization phase, utilization-based condition for the set of periodic synchronous messages has been deduced (Almeida 1999).

- Task Response Time-Based Scheduling Analysis

For the same set of periodic messages under synchronization phase, the sufficient schedulability conditions for worst-case phasing (all messages arrive in the critical instant) and for any phasing are researched (Almeida 1999, Wang 2000). Then the approach for worst-case message response time are constructed respectively.

6. SCHEDULING ALGORITHM FOR MINIMIZING RELEASE JITTER

To minimize the release jitter of message communication is the basic requirement of application. Minimizing release jitter becomes its important goal to be optimized if a scheduling algorithm meeting the real-time requirement. release jitter refers to the variation between the inter-scheduled instants of two consecutive instances of same message. For a periodic message τ_i , let $p_i^{\min} = \min_{k \geq 0} (C_i^{k+1} - C_i^k)$, $p_i^{\max} = \max_{k \geq 0} (C_i^{k+1} - C_i^k)$, where C_i^k denotes the instant when the k^{th} instance of periodic message τ_i .

In dynamic scheduling domain, there are lots of research on the topic of jitter, especially in the periodic task real-time scheduling in uni-processor. DCT (Distance constraint task) model have researched (Lin 1996). In DCT model, finishing time of any two continual instance of the same task is limited in a bounded value, which minimizes the release jitter caused by scheduler. In the context of real-time communication of DRTS, release jitter of end-to-end time guarantee is studied (Stankovic 1994). Further, a formal quantitative model for release jitter is proposed, and by

which a list of properties desirable for minimizing release jitter is presented (Baruah 1999).

FF and WorldFIP often adopt the synchronous phase, namely insert idle-time in ST. It brings two-fold effect: in one aspect, the advantage of using idle-time is to avoid the blocking caused by low priority messages for high priority messages, which minimizes the jitter of high priority; on another aspect, inserting idle-time spends communication capacity of system. Presently, both utilization-based and response time-based schedulability analysis available can't be used directly, but some ideas can be applied in the above paragraph and section 5.

7. SCHEDULING ALGORITHM FOR RELATIVE TASKS AND COMMUNICATION OF MANY SEGMENTS

The research of ST in the above section actually is confined within independent periodic messages and uni-processor (single segment). Within DRTS, in order to meet different requirements, many tasks are not independent, but interactive with each other and have relationships, such as synchronous phase, precedence and resource mutex and so on.

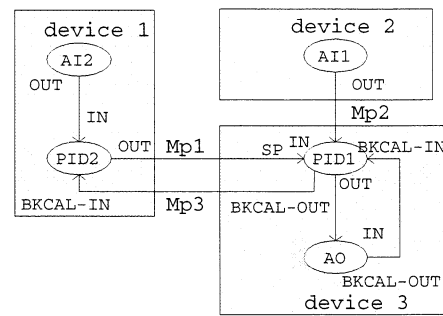


Figure 6. A cascade loop field devices configuration

Actually, it is known that FF system is composed of interrelated and independent FBs to perform control functions desired. Moreover the FBs can be cyclically scheduled to execute in a determined sequence and to transmit their external link messages on fieldbus at a determined time. And these FBs will be executed only after the required inputs are scheduled to be available. Accordingly, messages are no more independent either. And the precedence constraints of periodic messages have to be considered in the process of building STL.

Take a cascade control loop consisting of three field devices shown in Fig.6 as instance. There are 5 FBs (AI1, AI2, PID1, PID2, AO), among which there are 3 periodic messages need be transmitted on the fieldbus. According to the configuration of FBs indicated in Fig.6, PID2 is executed after AI2 finishes, then, periodic message Mp1 sends request to access the bus, i.e., Mp1 is released; after PID2 and AI1 finish, and periodic message Mp1 and Mp2 arrive device3, PID1 will be executed. This means that all periodic messages can't be released simultaneously - thus, the precedence constraints of periodic messages have to be considered in the process of building the STL.

In fact, almost all scheduling of related tasks are NP-complete (Mok 1983). There is not only no optimized

task scheduling algorithm existing, the running time is also untractable. To solve the problem of precedence restriction scheduling, an efficient algorithm is presented (Chetto 1990). Basic idea of the approach is to regulate the time parameter and turn the related tasks set J into an equivalent independent tasks set J*, then to construct an scheduling algorithm and do schedulability analysis using J*. The idea has been applied into FF and succeeds in solving the problem of precedence restriction scheduling for FBs, wherein a simple and effective heuristic scheduling algorithm to support real-time communication of periodic messages among FBs is proposed (Zhou 2001).

When application is distributed extensively or lots of messages need to communicate, it may adopt many segments to solve the requirements of message communication. Known from multi-processor scheduling, there is still not optimized task scheduling algorithm even if each task is independent. Furthermore, almost tasks have some relationship in fact. Because it is not only to decide when to execute tasks, but also to decide where to execute tasks, which involves in the allocation and scheduling of tasks, also includes the resource of processor and communication. It adds the difficulty of the problem. It has been proved that all about this problem are NP-Complete (Mok 1983). For the present, only some scattered achievement has been obtained in multiprocessor scheduling. Present research pays more attention to probable approaches like the heuristic algorithm and intelligent computation to get the sub-optimized result, for example Brand-and-Bound, Simulated Annealing, Genetic Algorithms *et al.* multiprocessor scheduling and multiple segment message scheduling are still open problem.

8. CONCLUSION

In order to meet real-time constraints of field devices in factory floor, this paper mainly investigates the problem of constructing schedule table, which is used in WorldFIP and FF. From the aspect of size of schedule table to schedule algorithms, this paper presents main results of the present time, and specially on response time, jitter, synchronization of periodic messages in field devices. However, with network penetrating into every aspect of industry applications, new real-time requirements are emerging. There are still a long way to walk for the problem and lots works to be done. Further, analysis integrated with real-time scheduling and control combined for a special application, is reported rarely, and the real-time quality of service needs be developed.

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